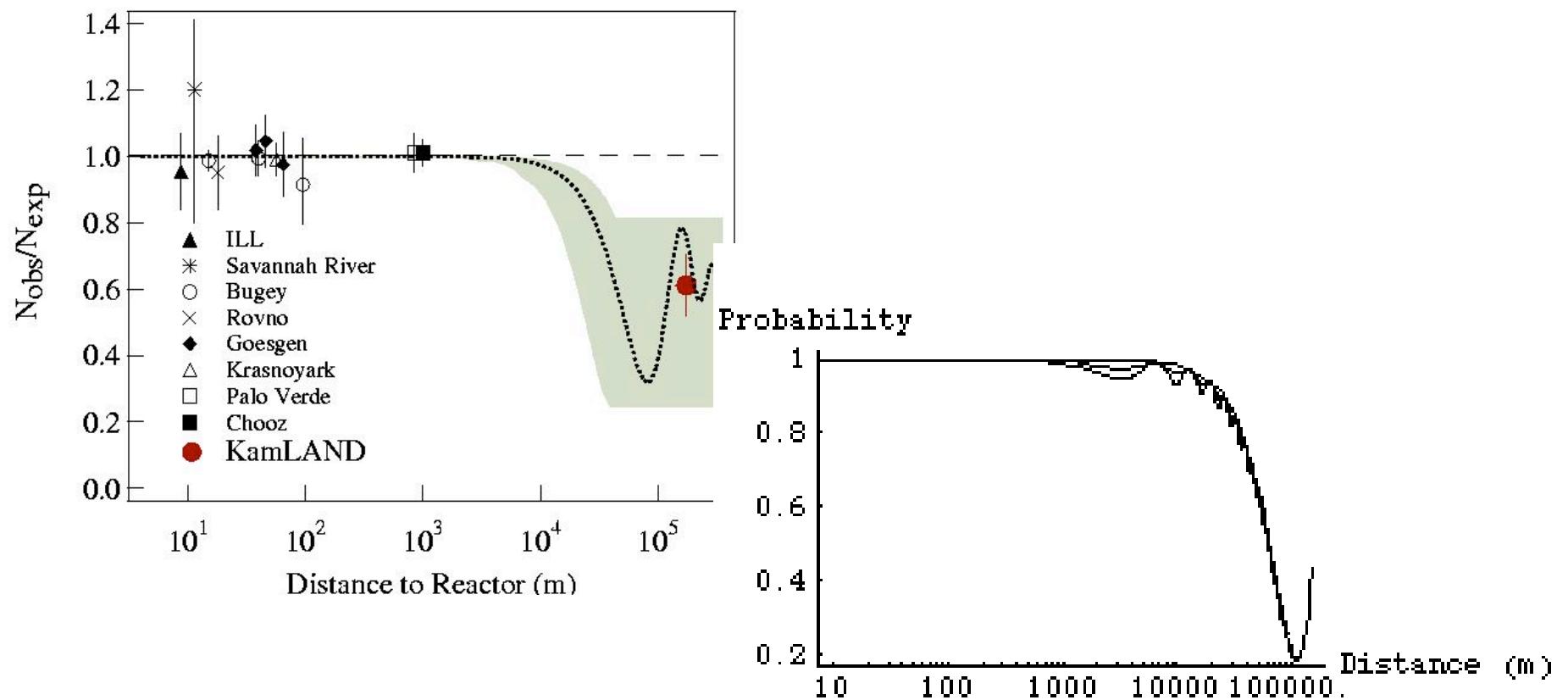


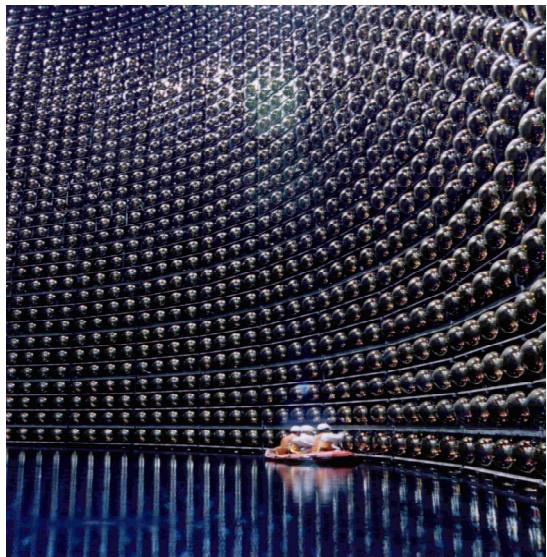
Reactor Neutrino Measurement of θ_{13}

**Searching for Subdominant Oscillations in $\nu_e \leftrightarrow \nu_{\mu,\tau}$
Measuring the Last Undetermined Neutrino Mixing Angle θ_{13}**



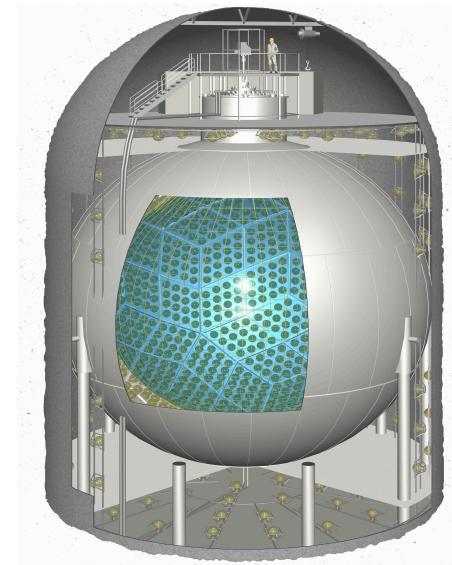
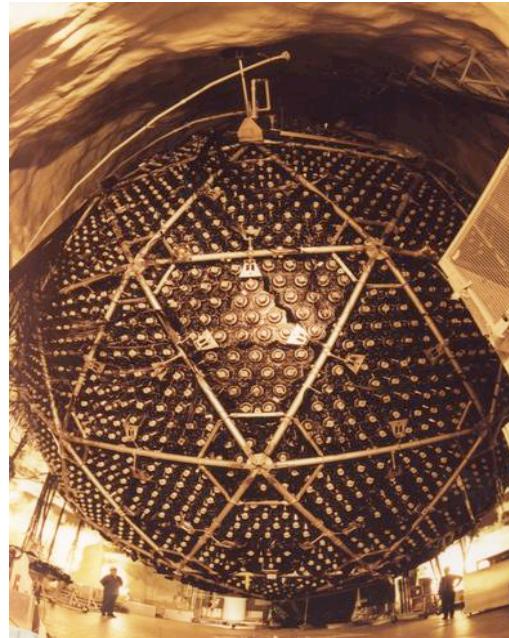
Recent Discoveries in Neutrino Physics

Non-accelerator experiments have changed our understanding of neutrinos



Atmospheric+Solar ☒
(Super-K)

Solar (SNO)



Reactor
(KamLAND)

- Neutrinos are not massless (mass is small: $m_{\bar{\nu}_e} < 0.0000059 m_e$)
- Evidence for neutrino flavor conversion $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu} \leftrightarrow \bar{\nu}_{\tau}$
- Combination of experimental results show that neutrinos oscillate

U_{MNSP} - Neutrino Mixing Matrix

Present and Future Measurements

| | | | |
|---|---|--|----------------------------|
| | Solar | $\theta_{12} = 30.3^\circ$ | <i>large</i> |
| | Atmospheric | $\theta_{23} = \sim 45^\circ$ | <i>maximal</i> |
| | Chooz + SK | $\tan^2 \theta_{13} < 0.03$ at 90% CL | <i>small ... at best</i> |
| No good ‘ad hoc’ model to predict θ_{13} . If $\theta_{13} < 10^{-3} \theta_{12}$, perhaps a symmetry? | | | |
| $U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$ $= \begin{bmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 & 1 & 0 & 0 & \cos \theta_{13} & 0 & e^{i\theta_{CP}} \sin \theta_{13} & 1 & 0 & 0 \\ \sin \theta_{12} & \cos \theta_{12} & 0 & 0 & \cos \theta_{23} & \sin \theta_{23} & 0 & 1 & 0 & 0 & e^{i\theta_{CP}} \sin \theta_{13} & 0 \\ 0 & 0 & 1 & 0 & \sin \theta_{23} & \cos \theta_{23} & e^{i\theta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} & 0 & 0 & e^{i\theta/2+i\theta} \end{bmatrix}$ | Dirac phase | Majorana phases | |
| solar present solar future | atmospheric present accelerator future | <i>Proposal for reactor θ_{13} experiment</i> reactor and accelerator future | 0 experiments future |

θ_{13} and CP Violation

For 3 Dirac neutrinos ...

$$U = \begin{pmatrix} 1 & 0 & 0 & | & 0 & \sim 1 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} & | & 0 & e^{i\theta_{CP}} \sin \theta_{13} \\ 0 & 0 & 0 & | & 1 & ? \end{pmatrix} \quad \begin{pmatrix} 0 & e^{i\theta_{CP}} \sin \theta_{13} & | & 0.85 & 0.51 & 0 \\ 1 & 0 & | & 0.51 & 0.85 & 0 \\ \sim 1 & 0 & | & 0 & 0 & 1 \end{pmatrix}$$

θ_{13} is key parameter for oscillation phenomenology since θ_{12} and θ_{23} are both large

θ_{13} determines whether CP violation is accessible

$$\text{CP proportional to } \theta_{13} \quad P(\bar{\nu}_e \rightarrow \bar{\nu}_e) / P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin \frac{m_{12}^2 L}{4E} \sin \frac{m_{13}^2 L}{4E} \sin \frac{m_{23}^2 L}{4E}$$

Next generation reactor experiments

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \propto \sin^4 \theta_{13} + \cos^4 \theta_{13} \left(\frac{1}{4} \sin^2(2\theta_{12}) \cdot \sin^2 \frac{m_{12}^2 L}{4E} \right)$$

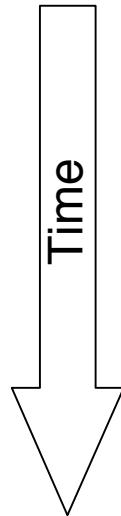
disappearance experiment but observation of oscillation signature

Future accelerator experiments

measurement of $\bar{\nu}_e \rightarrow \bar{\nu}_e$ and $\bar{\nu}_e \rightarrow \bar{\nu}_e$ yields θ_{13}, θ_{CP}
appearance experiment

Δm^2_{13} Neutrino Oscillation Experiments

Central Questions in Neutrino Oscillation Physics & The Role of Δm^2_{13}



1. What is the Δm^2_{13} coupling of ν_3 ? How large is Δm^2_{13} ?

Δm^2_{13} : *an opportunity for discovery*

2. What are Δm^2_{13} , Δm^2_{31} , Δm^2_{21} , Δm^2_{23} , Δm^2_{32} ?

Δm^2_{13} : breaks correlation, helps with *determination of parameters*

3. What is the mass pattern?

4. Is there CP?

Δm^2_{13} : *defines the future of accelerator neutrino experiments*

Next generation reactor experiments

$\sin^2 2\Delta m^2_{13}$ sensitivity: 0.005-0.01 @ 3E
no matter effects,
little parameter correlation

Future accelerator experiments

$\sin^2 2\Delta m^2_{13}$ sensitivity: 0.005
matter effects, correlation
sensitivity to Δm^2_{13}

Why Are Neutrino Oscillation Measurements Important?

Window on physics at high mass scales, physics of flavor, and unification:

- Why are neutrino masses so small?
- Why are the mixing angles *large, maximal, and small?*
- Is there CP violation, T violation, or CPT violation in the lepton sector?
- Is there a connection between the lepton and the baryon sector?

Matter-Antimatter Asymmetry ($\Box B \neq 0$) from Leptogenesis

MNS Lepton Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} 0.7 & 0.7 & <0.2e^{i\delta} ? \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

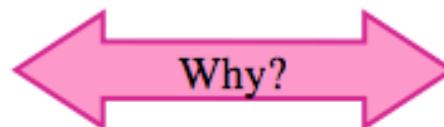
δ gives
CP violation

CKM Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003e^{i\delta} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

$$\begin{pmatrix} \text{big} & \text{big} & \text{small?} \\ \text{big} & \text{big} & \text{big} \\ \text{big} & \text{big} & \text{big} \end{pmatrix}$$



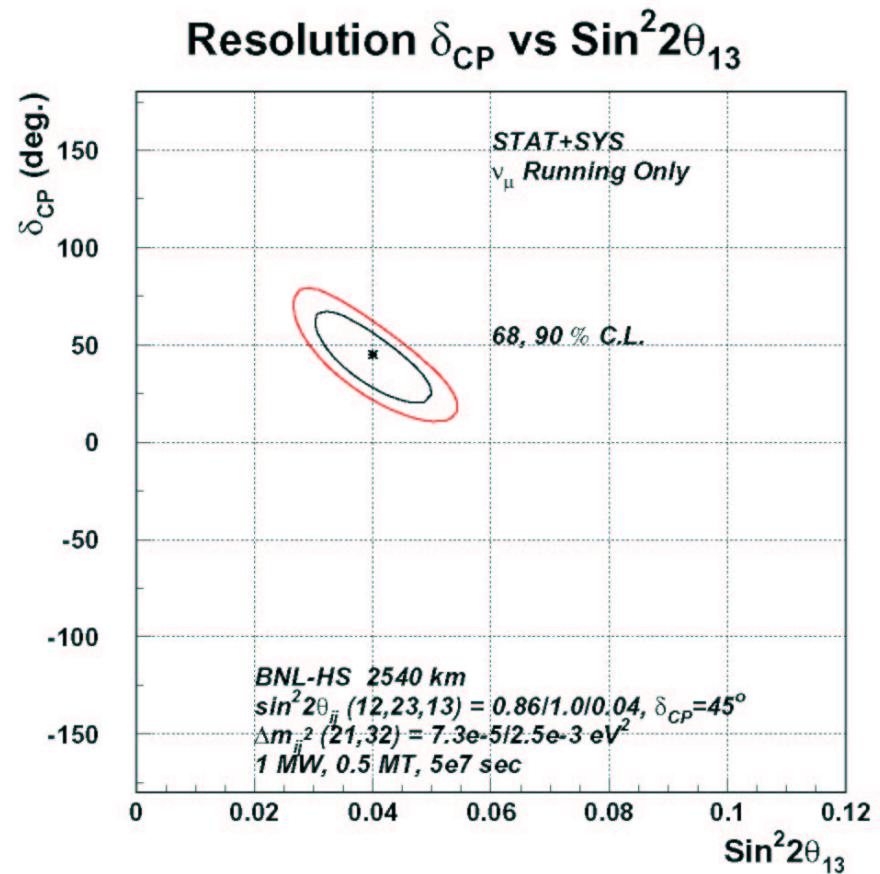
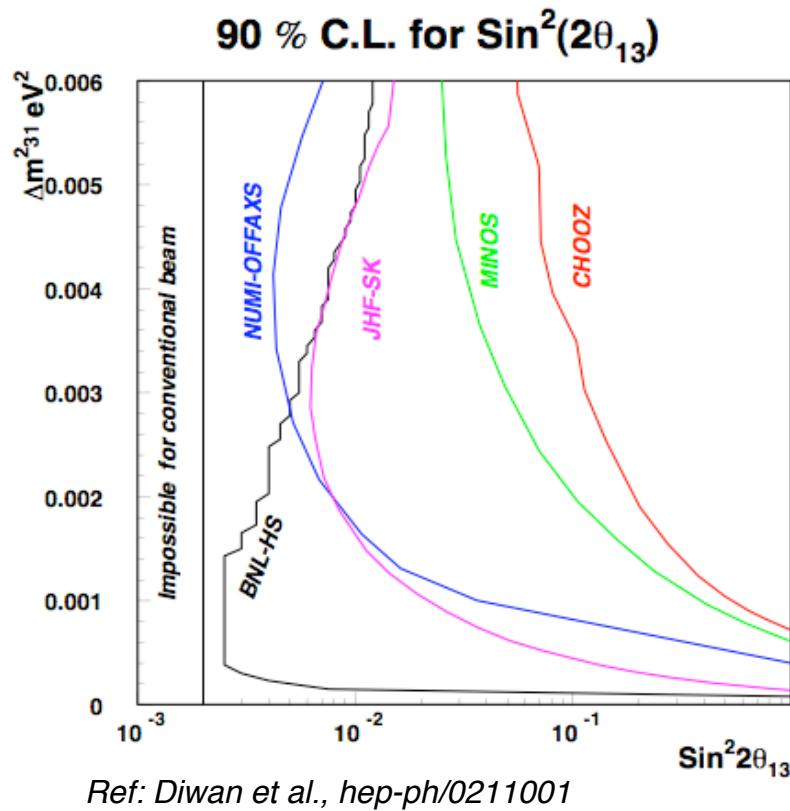
Why?

$$\begin{pmatrix} \text{big} & \text{small} & \text{very tiny} \\ \text{small} & \text{big} & \text{tiny} \\ \text{tiny} & \text{tiny} & \text{big} \end{pmatrix}$$

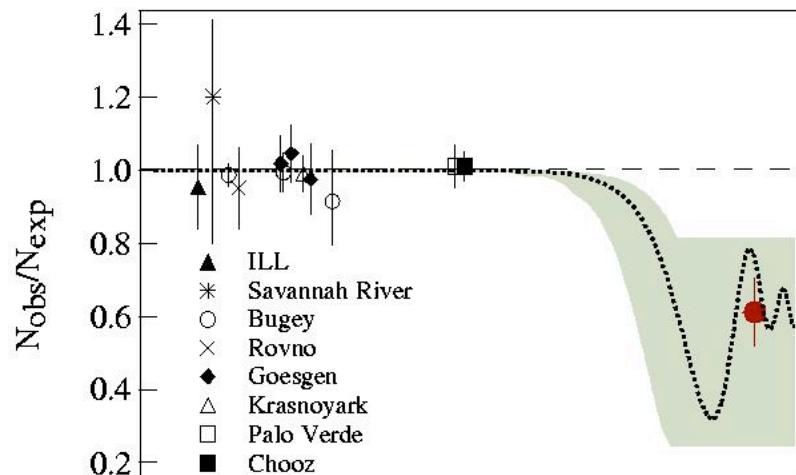
- Difficult to generate a baryon asymmetry $\Box B \neq 0$ using quark matrix CP violation
- Generate using CP or CPT violation in the lepton sector
 - \Box B-L processes then convert a neutrino excess to baryon excess
(Sign and magnitude may be able to generate the observed baryon asymmetry)

Δm^2_{31} Sensitivity of Accelerator Experiments

Measurement of Δm^2_{31} , θ_{13} and δ_{CP} yields Δm^2_{31} , θ_{13} , δ_{CP}



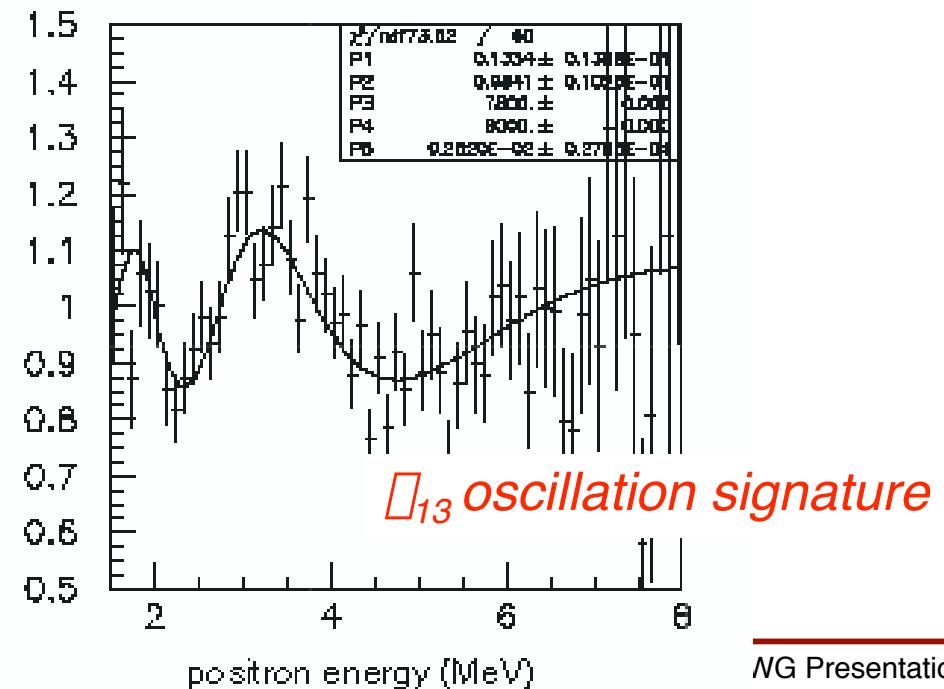
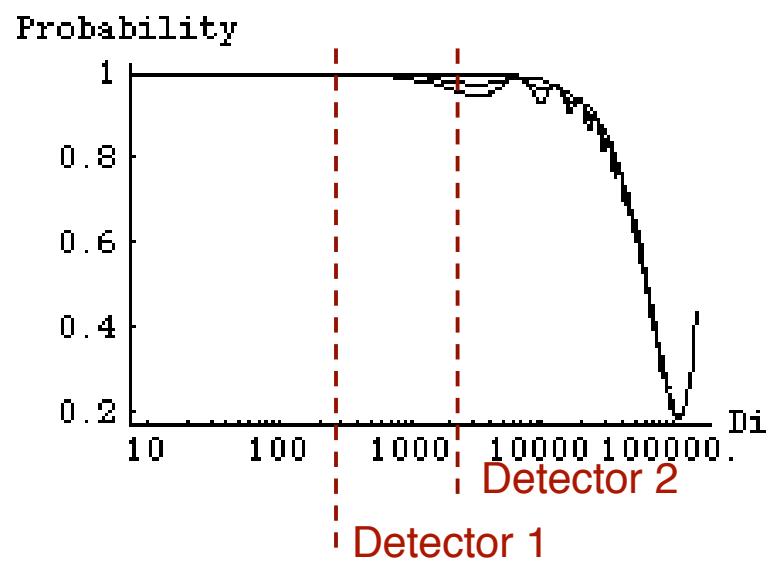
Reactor Neutrino Measurement of θ_{13}



Searching for Subdominant Oscillations in $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$

to measure the last yet undetermined neutrino mixing angle, θ_{13}

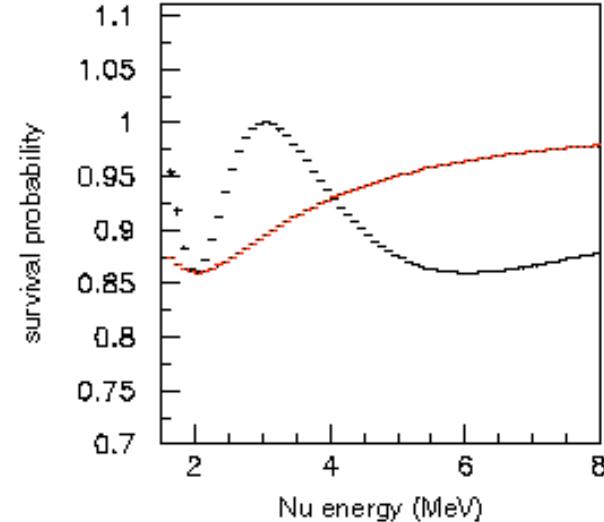
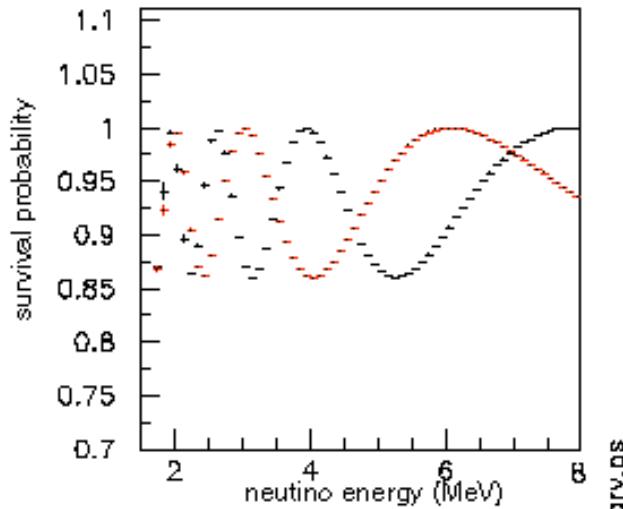
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \sin^4 \theta_{13} + \cos^4 \theta_{13} - 1 \cdot \sin^2(2\theta_{12}) \cdot \sin^2 \frac{m_{12}^2 L}{4E_{\bar{\nu}}}$$



MC Studies

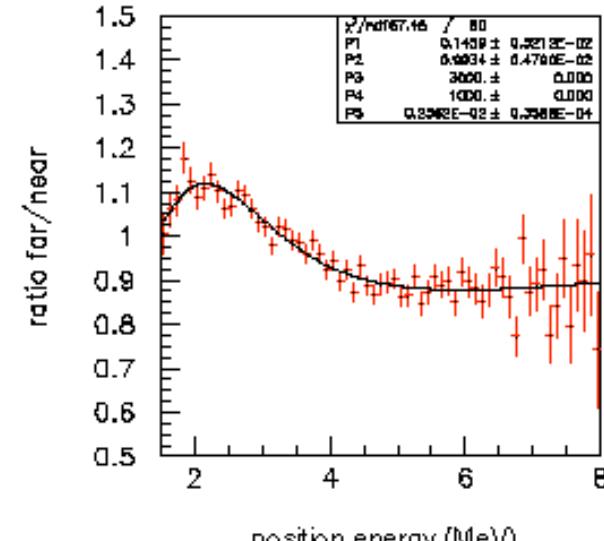
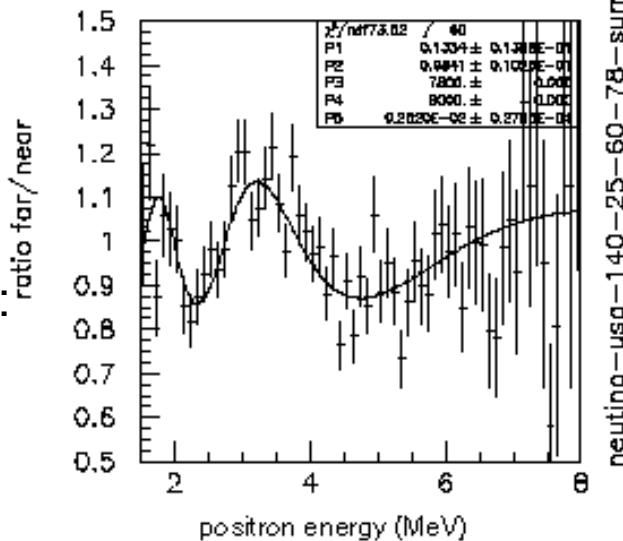
'far-far' $L_1=6\text{ km}$
 $L_2=7.8\text{ km}$

'near-far' $L_1 = 1\text{ km}$
 $L_2 = 3\text{ km}$

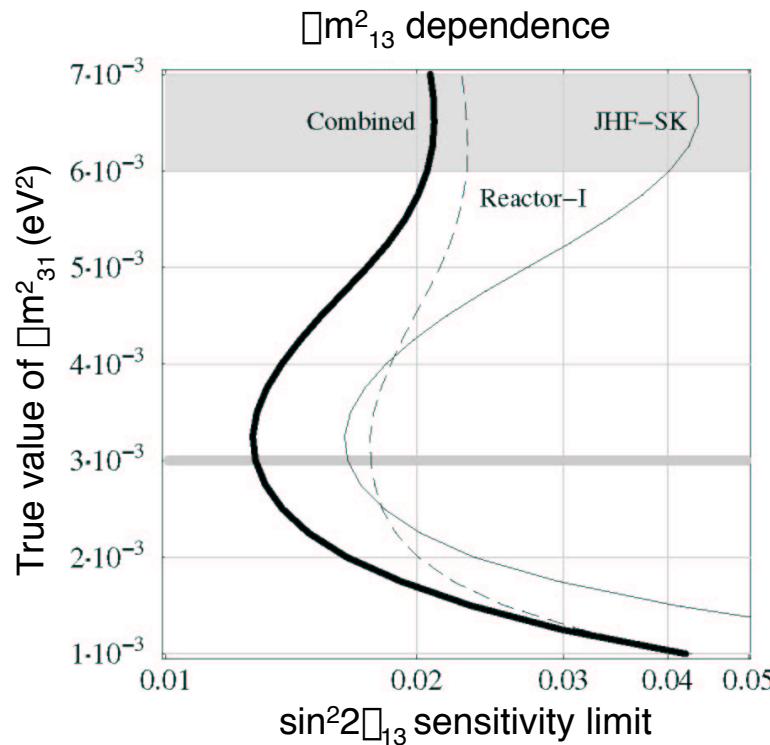


Normalization:
10k events at 10km

Oscillation Parameters:
 $\sin^2 2\theta_{13} = 0.14$
 $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$



Sensitivity and Complementarity of Δ_{13} Experiments

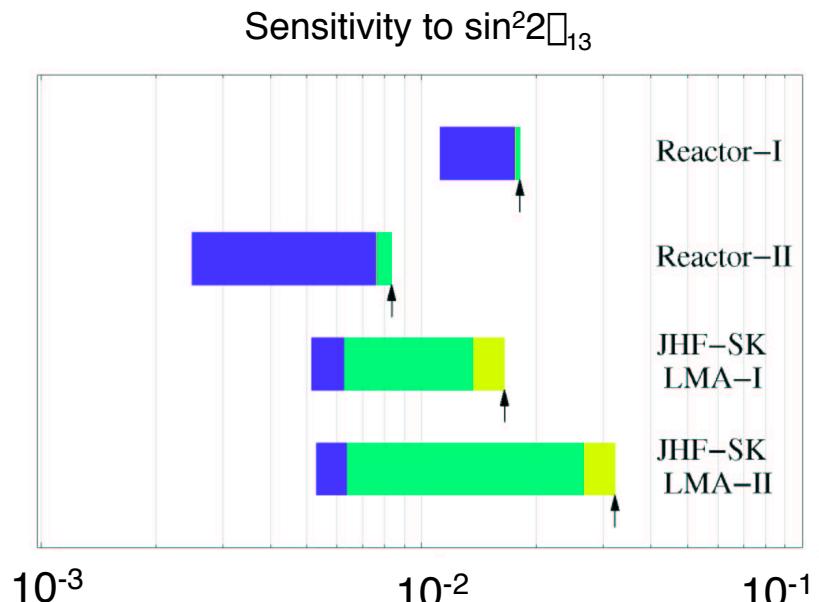


Reactor Δ_{13} experiment

No matter effect

Correlations are small, no degeneracies

Independent of solar osc. parameters $\Delta_{12}, \Delta m_{21}^2$



Ref: Huber et al., hep-ph/0303232

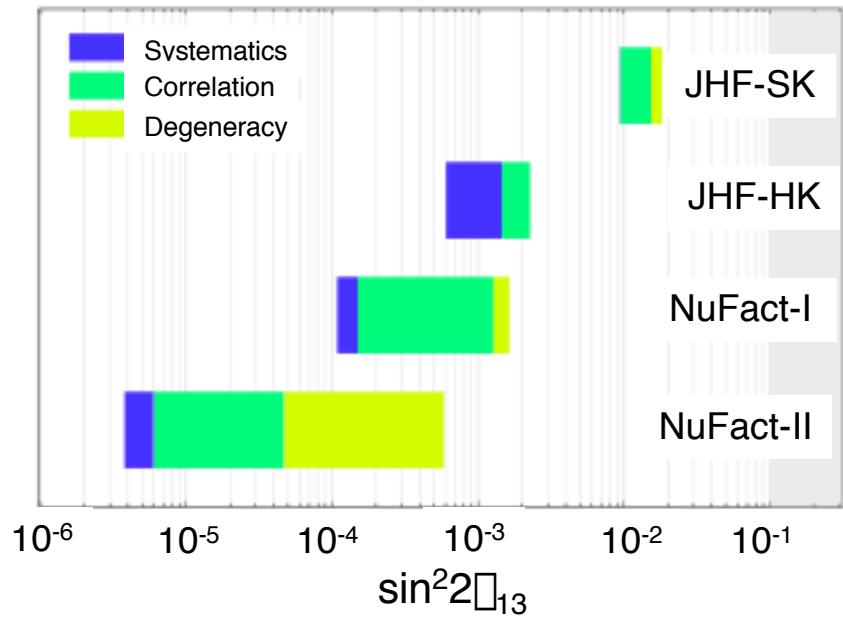
Accelerator experiments (superbeams)

Sensitivity to mass hierarchy and Δ_{CP}

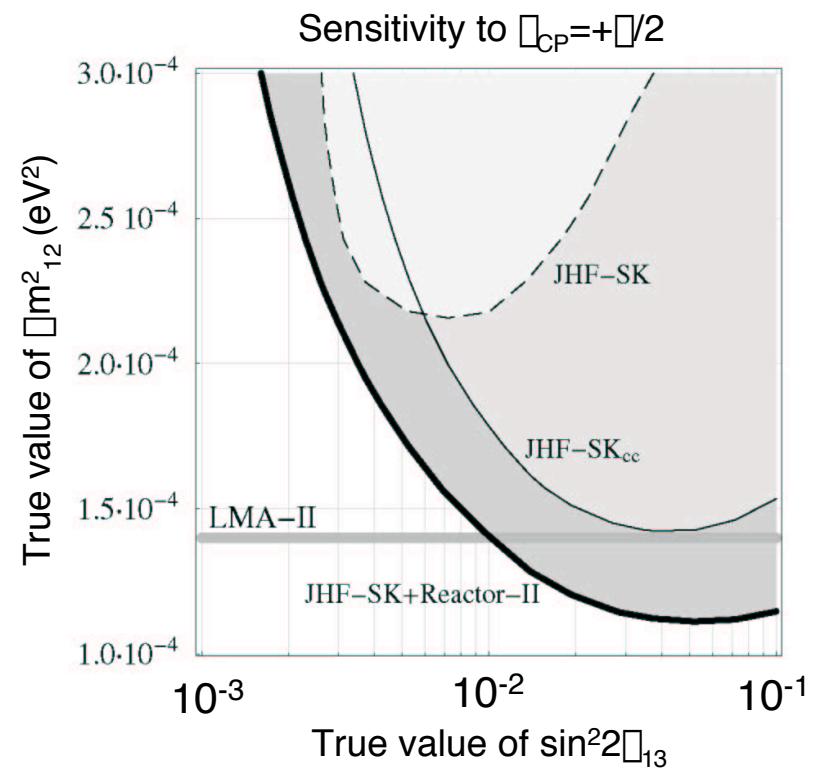
Sensitivity to Δ_{23}

Sensitivity to CP Violation

Long-Term Impact of a Reactor Δ_{13} Measurement



- Different sensitivity reductions by systematics
- Correlations & degeneracies lead to severe limitations in accelerator experiments
- Improvements by combining experiments



Ref: Huber et al., hep-ph/0303232

Site Requirements for Reactor Δ_{13} Measurement

1. **A reactor, or multiple-reactor complex**
2. **Sites for 2+ detectors** at distances of $\sim O(km)$ from the reactor site
3. **Detector overburden** for reduction of cosmic ray background

Man-made overburden or

Underground site

- mine
- railway tunnels

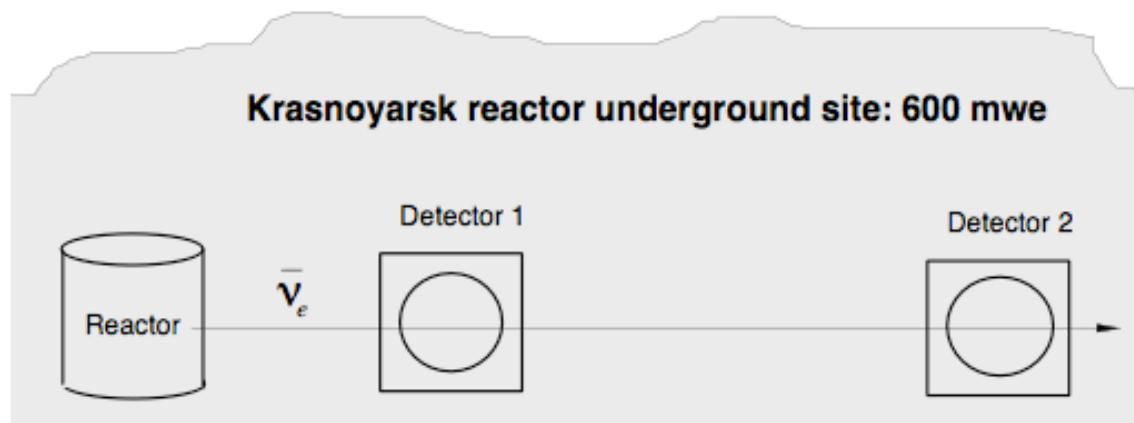


Tunnels:

- Preferably abandoned and deep
- Railroad tracks provide a convenient deployment mechanism
- Other obvious benefits include being able to switch the detectors.

Does a site like this exist?

Russian $\bar{\nu}_{13}$ Proposal at Krasnoyarsk: Kr2Det



115 m

1000 m

Target:

46 t

Rate: ~ 1.5×10^6 ev/year

~20000 ev/year

S:B

>>1

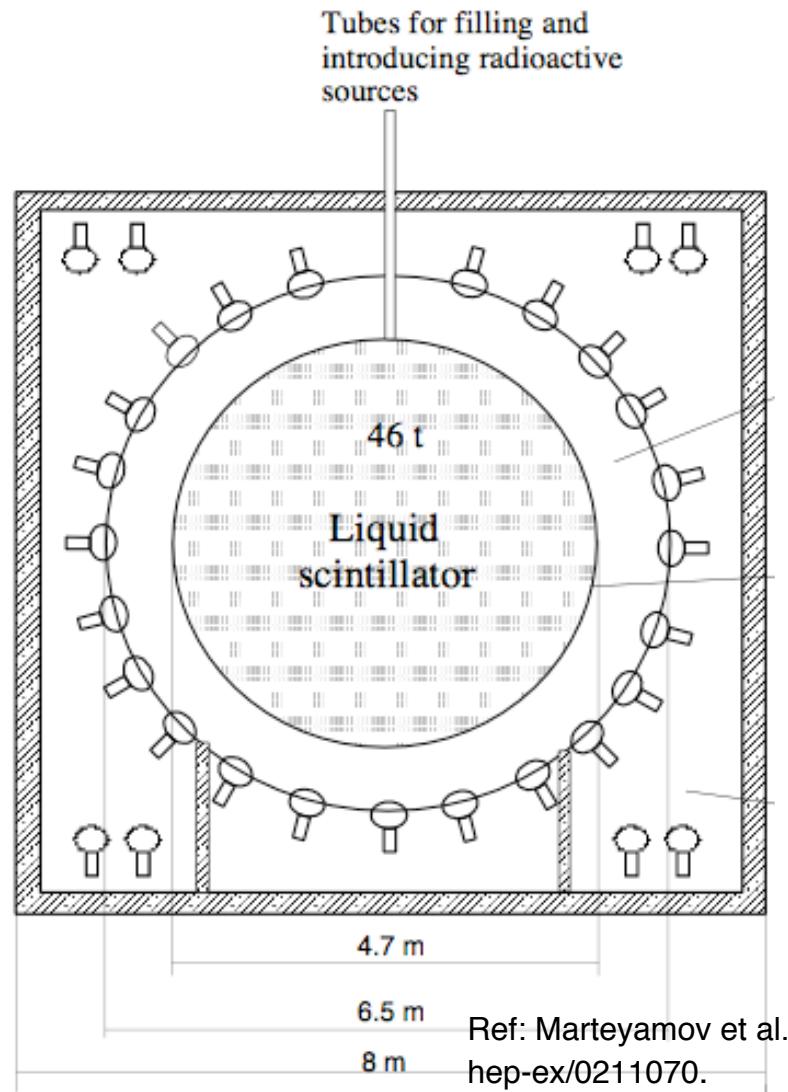
46 t

~10:1

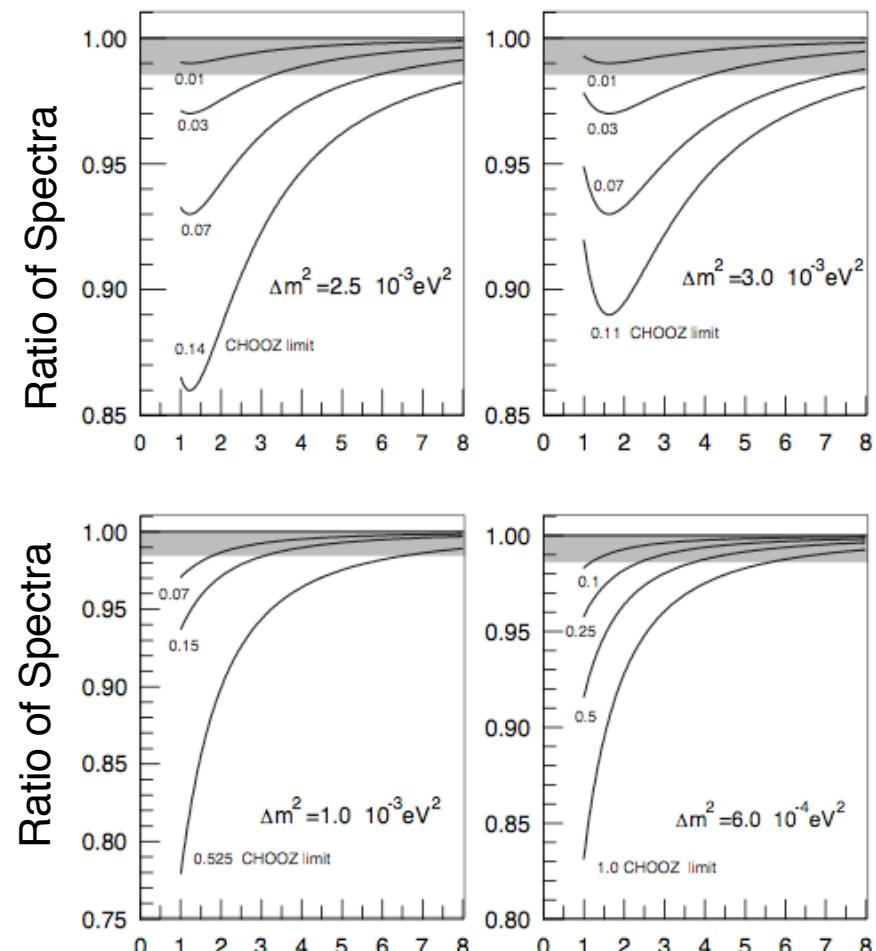


Ref: Marteyamov et al.
hep-ex/0211070

Russian $\bar{\nu}_{13}$ Proposal at Krasnoyarsk: Kr2Det



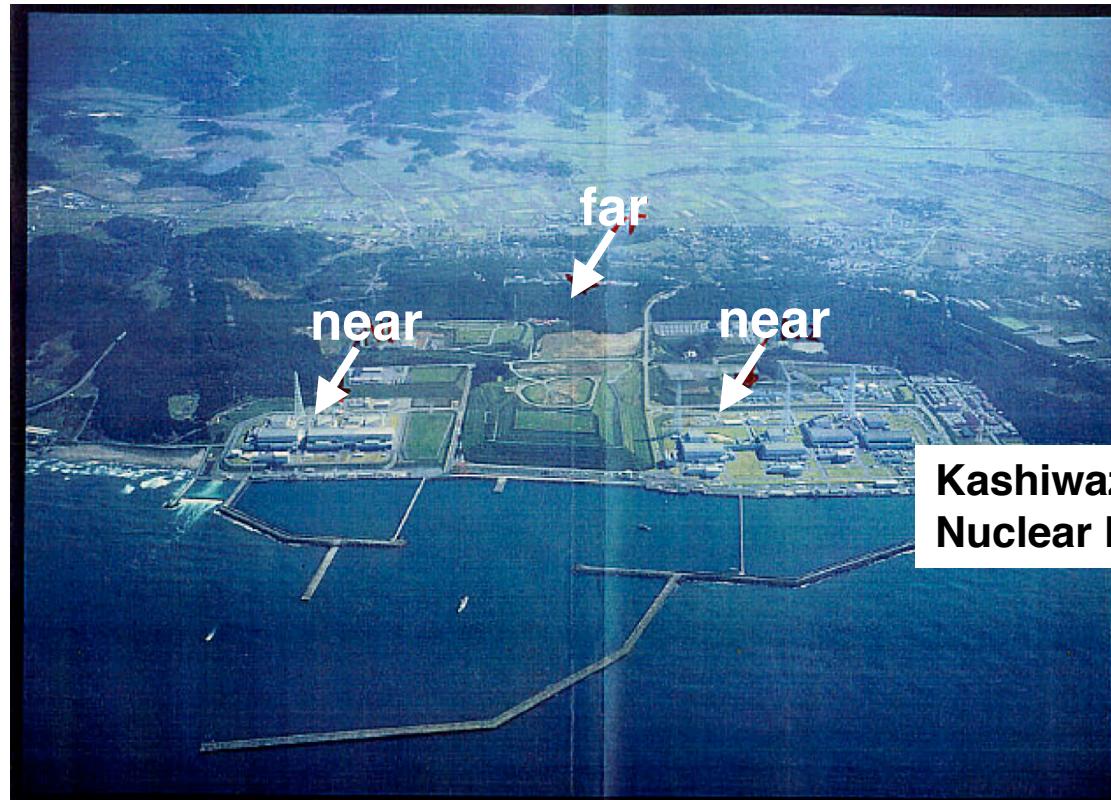
$L_{near} = 115 \text{ m}$, $L_{far} = 1000 \text{ m}$, $N_{far} = 16000/\text{yr}$



Japanese \square_{13} Proposal at Kashiwazaki

Kashiwazaki

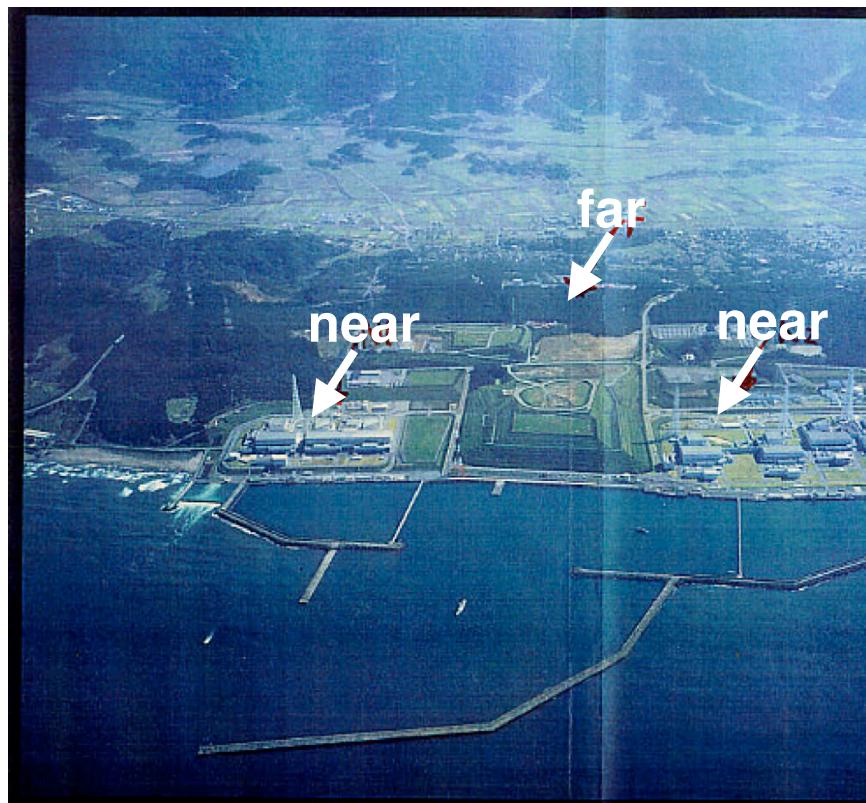
- 7 nuclear power stations
- requires construction of underground shaft for detectors



**Kashiwazaki-Kariwa
Nuclear Power Station**

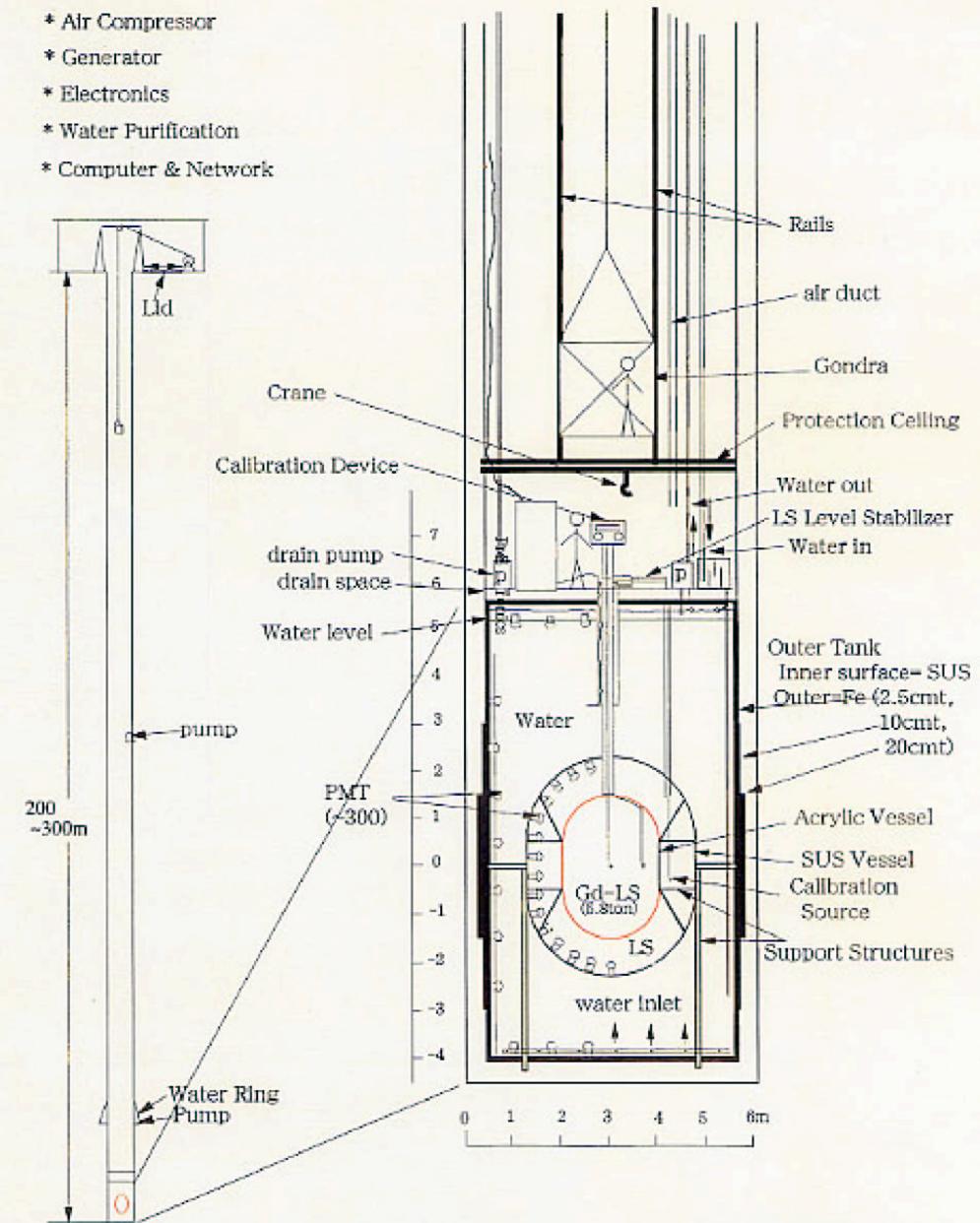


□₁₃ Proposal at Kashiwazaki



6m ϕ shaft hole with 200~300m depth

- * Crane
- * Air Compressor
- * Generator
- * Electronics
- * Water Purification
- * Computer & Network



A \square_{13} Reactor Experiment in the US?



| YEARS OF COMMERCIAL OPERATION | NUMBER OF REACTORS | AVERAGE CAPACITY (MDC) |
|-------------------------------|--------------------|------------------------|
| △ 0-9 | 2 | 1134 |
| ▲ 10-19 | 47 | 1092 |
| ▲ 20-29 | 55 | 779 |

Note: There are no commercial reactors in Alaska or Hawaii. Calculated data as of 12/00.

Several suitable candidate reactor sites in the US

Several underground sites and facilities under evaluation

Interest from several US groups

Argonne National Laboratory

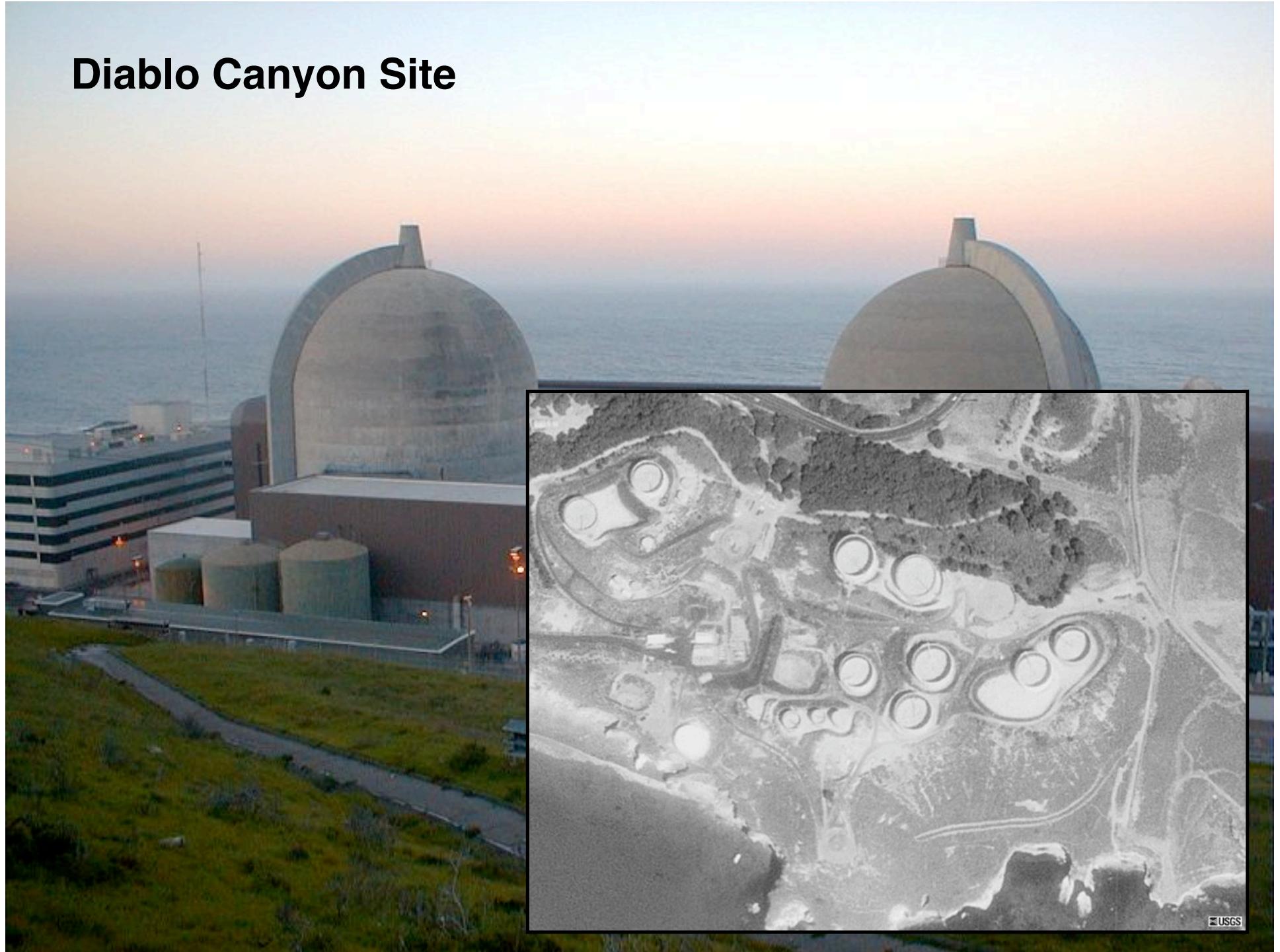
Caltech

Columbia University

(Fermilab National Laboratory)

.... *LBNL?*

Diablo Canyon Site



Diablo Canyon Site



- Two reactor site ($3.1 + 3.1 \text{ GW } E_{\text{th}}$) near hills on the California coast
 - Horizontal tunnel could give 600 mwe shielding
 - No reactor off time, may need new techniques to measure background
-
- For CHOOZ, a 5 ton liquid-scintillator detector at 1 km,
 $N = 2700$ in 200 days
 - For a 300-ton liquid scintillator detector at 4 km from Diablo Canyon reactors:
 $N \approx 12000$ in 300 days

Timescale and Size of a $\bar{\nu}_{13}$ Reactor Project

moderate scale (~\$30-40M)

*Estimated 5 years from LOI to run
Fraction of cost of accelerator experiment*

2005

2010

2015

Reactor $\bar{\nu}_{13}$

$\bar{\nu}_{13}$ run

JHF-SK, NuMI off-axis

CP precision studies

Reactor results will be on a timescale that complements off-axis results

From recent reports, conferences, and committees...

Lincoln Wolfenstein, March 2003

KITP Conference on Neutrinos: Data, Cosmos, and Planck Scale

Conclusions

Future for ν Mass + Oscillation

- * 1. Probe value of $\sin^2 \theta_{13}$
- * 2. Search for $\beta\beta$
= $\bar{\nu}_e \bar{\nu}_e \rightarrow e^+ e^-$ enough

HEPAP Facilities Committee, March 2003

"The observation of oscillation of one type of neutrino into another and the implication that neutrinos have been major discoveries of the past few years....The measurement [of θ_{13}] has important scientific potential"

Majorana

LBNL Neutrino Working Group, March 2003

"The most important experiment for determining the future direction of neutrino physics is the measurement of θ_{13} ...LBNL should pursue this option vigorously with the goal of leading a US experiment."

*Electric dipole moment
of e or n*

Conclusions: Reactor Measurement of θ_{13}

- Measurement of fundamental neutrino mixing angle with **discovery opportunity** and **long-term impact**.
 - Reactor experiment gives **clean measurement of $\sin^2 2\theta_{13}$** , with sensitivity of $\sin^2 2\theta_{13} < 0.005$ comparable to next-generation accelerator experiments.
 - Reactor θ_{13} experiment is a medium-size project. **Suitable for Berkeley**, natural **continuation of current program**.

- A timely θ_{13} measurement will define the future of accelerator θ physics.
 - Reactor experiments cannot replace superbeams. Accelerator experiments needed for determination of mass hierarchy and θ_{CP} .
 - Helps to resolve correlations and parameter degeneracies, important for determining the true values of $\sin^2 2\theta_{13}$ and θ_{CP} .

<http://theta13.lbl.gov/>

Further Information: θ_{13} Resource Site

References, Proposals, LBNL Activities, Workshops, ...

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric } \nu} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 0 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor + accelerator } \nu} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar + reactor } \nu}$$

<http://theta13.lbl.gov/>

